

INFRARED EXTINCTION AND THE INITIAL CONDITIONS FOR STAR AND
PLANET FORMATION

Grant NAG5-9520

Final Report

For the period 1 May 2000 through 31 October 2004

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Infrared Extinction and the Initial Conditions for Star and Planet Formation

This grant funded a research program to use infrared extinction measurements to probe the detailed structure of dark molecular clouds and investigate the physical conditions which give rise to star and planet formation. The goals of the this program were to: 1) acquire deep infrared and molecular-line observations of a carefully selected sample of nearby dark clouds, 2) reduce and analyze the data obtained in order to produce detailed extinction maps of the clouds, 3) use the results to measure and quantitatively describe the physical conditions of the dense gas and dust that produce stars and their accompanying planetary systems in molecular clouds. The goals of this project were met and exceeded as described below.

1)- The infrared data for the project were obtained in a number of observing runs using the 3.5-meter NTT and 8-meter VLT telescopes of the European Southern Observatory in Chile and the 1.2-meter telescope of the Smithsonian Astrophysical Observatory in Arizona, the 10-meter Keck telescope in Hawaii, the 6.5-meter MMT of the Smithsonian Astrophysical Observatory in Arizona, and the NASA Hubble Space Telescope. The molecular-line data was obtained in three runs using the IRAM 30-meter telescope in Spain and one run with the ESO-15 meter millimeter-wave telescope in Chile. Millimeter-wave continuum measurements were obtained with the 15-meter JCMT in Hawaii.

2)- Considerable effort was expended to reduce the infrared imaging observations including the development of custom software to produce high quality photometry and source astrometry. All the millimeter-line data was reduced using standard reduction routines. The highlights of the infrared analysis were the production of detailed extinction maps and the construction of profiles of the density structure of the B68, Coalsack, B335 and Lupus clouds.

3)- The principal scientific accomplishments of this research program include the following:

We were able to use our infrared observations to determine the density structure of the B68 cloud to an unprecedented level of precision. This led to a major breakthrough in the study of molecular cloud structure. For the first time we have been able to characterize the structure of a dark cloud in a detail only exceeded by that known for a star. We determined that the cloud's structure is exquisitely well described by the equations of a Bonner-Ebert sphere (a pressure confined isothermal sphere). We were able to show that the cloud is very nearly in equilibrium with the internal thermal pressure of the cloud balancing gravity and the external pressure of the surrounding interstellar medium. We were able to determine for the first time the gas-to-dust ratio in a dense cloud core. We also demonstrated a new method to determine extremely precise distances to such clouds by combining knowledge of the properties of Bonner-Ebert Spheres with our infrared and millimeter-wave observations.

The analysis of the molecular-line observations of B68 led to the recognition of a possible new dynamical state for molecular clouds in which the cloud appears to be experiencing small amplitude, non-radial oscillations around a state of stable equilibrium, similar to those experienced

by stars. We also found that the B68 cloud is supported against gravitational collapse by thermal pressure alone, the only molecular cloud yet known for which this is demonstrated to be the case. In addition we were able to describe the chemical structure of the cloud in clear detail. We discovered among the first compelling pieces of evidence for differential gas-phase depletion of molecular species in a cold cloud core, including the first detection of the depletion of the nitrogen bearing species N_2H^+ .

We produced very deep extinction measurements of the structure of the famous Globule 2 in the Coalsack cloud which in combination with molecular-line measurements enabled the detailed investigation of the nature of this starless dense core. The high angular resolution afforded by our deep infrared observations, enabled us to completely resolve the structure of this globule for the first time. We discovered the globule to be the least centrally condensed of all objects we have studied and moreover to be characterized by a strong ring structure in its central regions. Our analysis suggested that the ring was a configuration that was out of equilibrium and likely unstable to inward implosion. As a result our observations appear to have uncovered one of the earliest stages in the evolution of a dense molecular cloud core. This enabled us to accomplish the primary science goal of this program, a quantitative characterization of the initial conditions of star formation.

We produced the first extinction measurements obtained with the Hubble Space Telescope. These observations enabled us to prescribe the detailed structure of the B335 protostellar cloud and are the first to demonstrate the effect of molecular outflow on the radial distribution of density in a protostellar cloud. These observations also indicated that a cloud that has evolved to produce a protostellar object is characterized by a very steep radial density gradient and relatively large center-to-edge density contrast compared to starless clouds such as B68 and Coalsack Globule 2.

Our deep infrared observations resulted in the first determination of the radial density structure of dense cores within a filamentary molecular cloud. Our observations of the Lupus 3 dark cloud complex produced maps of the structure of five dense cores within the cloud. We found a spatial gradient of star forming activity in the cloud which was directly correlated with the structure of its dense cores. We found evidence for quasi systematic structural evolution of dense gas from starless cores to star forming cores. Specifically we determined that the center-to-edge density contrast of a dense core increases as star formation activity within it increases. This appears to confirm the results that were suggested by our studies of the B335, B68 and Coalsack globules.

Submillimeter continuum observations of IC 5146 were combined with our deep extinction survey of IC 5146 to map the temperature structure in the cloud and its individual cores. These observations have enabled us to simultaneously map the dust emissivity in the cores and have resulted in direct evidence for grain growth in the cold pre-stellar cores within the cloud.

4) Papers that were published or submitted for publication resulting from research supported by this grant:

1- "Internal structure of a cold dark cloud inferred from the extinction of background starlight", Alves, J. A., Lada, C.J. & Lada, E.A. 2001, *NATURE*, 409, 159.

- 2- "Molecular Excitation and Differential Gas-Phase Depletions in the IC 5146 Dark Cloud", E.A. Bergin, D. R. Ciardi, C.J. Lada, J. Alves, & E.A. Lada 2001, *The Astrophysical Journal*, 557, 209 .
- 3- "Structure of Protostellar Collapse Candidate B335 Derived from Near-Infrared Extinction Maps", D.A. Harvey, D.J. Wilner, C.J. Lada & P.C. Myers 2001, *The Astrophysical Journal*, 563, 903.
- 4- "Seeing Light Through the Dark" , J. Alves, C. Lada & E. Lada, 2001 *ESO Messenger*, 103, 1.
- 5- "N₂H⁺ and C¹⁸O Depletion in a Cold Dark Cloud", 2002 E.A. Bergin, J. Alves, & T. Huard & C.J. Lada, *The Astrophysical Journal*, 570, L101-L104.
- 6- "The Dynamical State of B68: A Thermally Supported Pulsating Dark Cloud", Lada, C.J., Bergin, E.A., Alves, J.F. & Huard, T.L. 2003 , *The Astrophysical Journal*, 586, 286.
- 7 -"Dust properties of the dark cloud IC 5146 – Sub millimeter and NIR imaging", Kramer, C., Richer, J. Mookerjee, B. Alves, J. & Lada, C.J. 2003, *Astronomy and Astrophysics*, 399, 1073.
- 8 –"Envelope Structure of Starless Core L694-2 Derived from a Near-Infrared Extinction Map", Harvey, D.W.A., Wilner, D.J., Lada, C.J., Myers, P.C. & Alves, J. 2003, *The Astrophysical Journal*, 598, 1112.
- 9- "Discovery of a Dusty Ring in the Coalsack: A Dense Core Caught in the Act of Formation?", Lada, C.J., Huard, T., Cruz, L. & Alves, J. 2004, *The Astrophysical Journal*, 610, 303.
- 10 – "From Dusty Filaments to Cores to Stars: An Infrared Extinction Study of Lupus 3", Teixeira, P.S., Lada, C.J., & Alves, J.F. 2005, *The Astrophysical Journal*, in press.